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SPECTROSCOPIC UV IMAGER SYSTEMS FOR STUDY OF ATMOSPHERIC CONTAMINATION

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Rockets generate pollutant species in their flight through the troposphere and stratosphere. To assess the environmental impact of such species, it is necessary to know the concentrations and the lifetimes of the foreign species and the chemistry which they undergo in the atmosphere. This program was to design and use instruments to gather data to determine the species, concentrations, and lifetimes of these foreign species. The measurement program was based on measuring the emission and absorption spectrum of the exhaust gases to determine the components in the gas cloud. This final report covers the first phase of a multi-year contract to develop the spectroscopic ultraviolet imager instrument system. Funding was limited and the contract eventually cancelled due to the severe cutback in funding for such research. This final report must be viewed in this light, a summary of the work at the beginning of an instrument design program.

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SPECTROSCOPIC UV IMAGER SYSTEMS FOR STUDY OF ATMOSPHERIC CONTAMINATION

INTRODUCTION

This final report covers the first phase of a multi-year contract to develop spectroscopic ultraviolet imager systems for the measurement of atmospheric contamination from rocket engine exhaust and other aircraft. The funding was limited and the contract eventually cancelled due to the severe cutback in funding for such research within the Air Force Phillips Laboratory. This final report must be viewed in this light, a summary of the work at the very beginning of a program.

Background

Rockets and jet aircraft generate pollutant species in their flight through the troposphere and stratosphere. In order to assess the environmental impact of such species, it is necessary to know the concentrations and the lifetimes of the foreign species and the chemistry which they undergo in the atmosphere. The proposed research is to design and use instruments to gather data needed to determine the species, concentrations, and lifetimes of these foreign species.

The proposed measurement program is based on measuring the emission and absorption spectrum of the exhaust gases. This spectral data can then be analyzed to determine the components in the gas cloud.

The first step in the program was the systems analysis and design of a spectrographic photometer system suitable for making absorption spectra measurements down stream of a horizontal mounted rocket engine. employing light sources to facilitate obtaining absorption spectra. Dr. Theodore Williams, our consultant, visited Phillips Laboratory, to discuss the system tradeoffs with the Technical Officer, Dr. C. Stergis, and to get further direction as to the near term goals of the program. It was agreed that the focus would be on absorption spectroscopy.

In making spectral absorption measurements, the sensitivity is maximized by choosing the spectral resolution of the instrument to be at least as high as the absorption line width. By doing so,

the contrast between the spectral absorption feature and the continuum (background) is maintained. That is to say, the spectrographic instrument should resolve (not blur) the absorption line.

In the case of atmospheric contamination, one is dealing with a relatively cool gas and the absorption lines are quite narrow, <0.1 nm. This became the starting point in choosing the spectrograph focal length, diffraction grating ruling pitch and the image sensor resolution.

In measuring absorption lines the brightness of the illuminating source is a cardinal factor along with the opacity of the gas in the spectral region adjacent to the absorption line. The opacity is unknown and most likely variable. Therefore we intend to purchase a commercial portable lamp having a relatively smooth spectrum and with a brightness as high as can be accommodated within the budget.

Dr. Theodore Williams, our consultant, investigated Acton and Spex spectrographs, choosing the Spex HR460 because of its superior imaging over the focal plane format. The HR460 characteristics are:

Focal Length	455 mm
Entrance Aperture Ratio	f/7 with 58 x 58 mm grating f/5.3 with 76 x 76 mm grating
Scanning Range	0-1300 nm
Multichannel coverage with 1200 g/mm grating	45nm over 25.4 mm width
Flat Field Area	25.4 wide x 15 mm high
Spectral Dispersion with 1200 g/mm grating	1.76 nm/mm
Spectral Resolution with 1200 g/mm grating	0.07 nm at 546 nm

A 450 Watt Xenon illumination source was purchased from Oriel. This lamp has a relatively flat spectrum between 300 and 800 nm.

The problem may be to provide a suitable power source when in the field. A portable gasoline engine driven generator may be the answer. The weight of such units is a problem, in terms of freight charges.

This spectrographic instrument has been designed with the primary application being to measure with high spectral resolution the absorption spectra of the gas in the exhaust of a rocket engine after the gas has cooled. There were two possibilities for doing this; static firings of rocket engines and in flight

measurements.
The static firing tests would employ the high power Xenon lamp and the measurements in flight would employ background stars. It was conceded that the use of stars was risky, due to the dependence on stars of sufficient brightness being in the background against which the rocket plume would be viewed. Even so, it seems worth pursuing because it provides data that is otherwise inaccessible or very difficult to obtain without great expense. One could also envisage a high altitude aircraft carrying a light source.

While the spectrograph was selected with absorption spectra in mind, it can also be used for emission spectra acquisition.
In the case of weak emission in the upper atmosphere, the slit could be opened up to maximize the amount of light gathered and rely on the fact that the emission lines are narrow and spaced far enough apart spectrally to be distinguished from each other in spite of the wide slit.

It should also be noted that while this spectrographic instrument has been designed with ground based observations in mind, it is also suitable for making observations from airborne platforms such as balloons and airplanes.

HAARP is a Phillips Laboratory program, involving measurements of stimulated atmospheric emission. The applicability of the slit spectrograph to this program is discussed below. This analysis is, of course, also applicable to auroral observations and upper atmosphere "lightning" phenomena.

SLIT SPECTROGRAPH INSTRUMENT FOR HAARP and RELATED APPLICATIONS

The SPEX HR460 spectrograph is f/5.3 with focal length of 455mm. A telescope of the same focal length and focal ratio would have a diameter of 455/5.3 = 86 mm = 3.4 inches.

The spectral dispersion with the 2400 grooves/mm grating is 0.88 nm per mm. Assume a slit width of 0.5 mm then the spectral resolution would be o.44 nm = 4.4 Angstroms. The Tektronix 1024x1024 pixel CCD is 24.6 mm wide and would have overall coverage of 216 Angstroms. With the 1800 grove/mm grating the spectral resolution for 0.5 mm slit would be 5.85 A and the overall coverage would be 288 A.

The image sensor could also be 24.6 mm tall, resulting in a slit area of 12.3 sq.mm. for the spectral pixel. At a focal length "F" of 455 mm, the angle subtended by the slit length is 24.6/455 = 0.054 radian and the slit width is 0.0011 radian, and the slit subtends a solid angle of 5.9 x 10E-5 steradian. The emitting area "a" at 300 km altitude corresponding to 5.9 x 10E-5 steradian is

$a = 5.3 \times 10E10$ sq.cm.

This is the radiating source focused on the slit.

The collecting aperture with a diameter "d" subtends a solid angle equal to

$$(d/H)^2$$

where "H" is the altitude of the radiating source.

$$\text{The image plane pixel exposure} = tRK(a)\left(\frac{d}{H}\right)^2 \qquad (1)$$

While this form of the equation is a logical way to calculate the exposure, it can be simplified by recalling that

$$a = \frac{\text{slit area}}{F^2} H^2$$

Substituting in (1) for "a',

$$\text{Exposure} = tRK\left(\frac{\text{slit area}}{(F/d)^2}\right) = tRK\left(\frac{\text{slit area}}{(f/\#)^2}\right)$$

One sees from this form of the equation that the way to increase signal is to increase the slit area and or reduce the focal ratio.

If one doubled the focal length of the telescope, keeping the f/# the same, the diameter of the telescope doubles and the telescope would collect 4 times the light. However the slit now subtends an area of the sky that is 1/4 the size, so there is not net gain. The only advantage would be in improving the spatial resolution on the sky.

If the slit is increased in width and height by a factor of two at the same time the telescope focal length and aperture are increased by a factor of two, then there is a net gain of a factor of 4 because the slit area is increased by this amount. The spatial resolution remains the same. The spectral resolution element is the image of the slit, so, for the same spectral resolution with the larger slit, one must increase the grating ruling density by a factor of two, or increase the focal length and grating size by a factor of two. The detector size must grow also to maintain the spectral coverage.

In the special case where the radiation consists of narrow

emission lines, such as what is expected in HAARP, and if the spectral lines are far enough apart that two are not subtended by the image of the slit, then the grating need not be increased by a factor of two.

One should note that the background signal from any radiation continuum such as sunlight will be minimized by increasing the spectral dispersion. One sees that optimizing the instrument benefits from knowing, in general, the spectrum of the background and stimulated radiation of interest.

Now, consider reducing the focal ratio (f/#) by a factor of two, by doubling the diameter of the aperture while keeping the focal length fixed. One collects four times the light from the same size radiating area in the sky as before. The grating of the spectrograph must also double in diameter in order to subtend this faster (wider) optical beam.

Reducing the f/# seems the better path to improving sensitivity. However, the optical aberrations generally grow as the focal ratio is reduced. Since spatial resolutions not a primary concern in HAARP, this may be the direction to go.

Observations Using the Spectrograph as it exists.

The existing spectrograph is f/5.3
For the 0,5 mm wide, 24.6 mm tall slit discussed above the slit area is 0.123 sq.cm.

Let: t=10 sec, K=0.3, Qe=0.6 electrons/photon and

$R = 8 \times 10^4$

Exposure = ~600 photoelectrons/R

Assume a 5R signal on a 10R background and a 10 second exposure. Then the total slit signal is (5 + 10)10 x60=9,000 photoelectrons. The shot noise limited signal to noise ratio would be

$$S/N = \frac{3{,}000}{(9{,}000)^{1/2}} = 31$$

The readout noise of the CCD would be in the order of ~15 electrons rms per readout. One must also consider the dark current of the CCD. The slit is 21 pixels wide and 1024 pixels tall. Assuming that the CCD is cooled to reduce the dark current to 0.1 electron per second per pixel, the signal to noise ratio would become

$$S/N = \frac{3000}{(9000 + 22{,}500 + (15)^2)^{1/2}} = 17$$

This assumes the pixels are binned prior to readout to minimize the small signal charge transfer problems in reading out the CCD.

INSTRUMENT DEVELOPMENT STATUS

The SPEX Model 460MST, 0.46 meter, f/5.6 Imaging Monochromater/Spectrograph was purchased and received. An Oriel 450 watt Xenon UV Lamp with power supply was also purchased and received. Mechanical parts were designed and fabricated for mounting the Lamp Housing onto a tripod to facilitate pointing.

Mechanical parts were designed and fabricated for mounting an existing Nye 6 inch diameter, all reflecting telescope and a remote controlled filter wheel in front of the entrance slit of the spectrograph. A special mount was also designed and built to allow the entrance slit to be viewed via an eyepiece so that the user could insure that the image of interest is imaged onto the entrance slit. The mounting of the spectrograph to a baseplate for attachment to a heavy duty tripod has been partially designed and some parts fabricated.

A digital television camera with a camera head suitable for interfacing to the spectrograph was ordered but canceled when funding did not become available.

Appendix A

ANALYSIS OF THE GENERAL PROBLEM OF MEASURING THE BRIGHTNESS OF A FAINT EXTENDED SOURCE AGAINST A BRIGHTER BACKGROUND

In attempting to measure the brightness of an extended source against a brighter background, one is limited by the statistical "quantum noise" associated with the background. For example, the rms noise in the background is equal to the square root of the number of photoelectrons detected in the measurement, i.e. the number of photoelectrons per pixel in the exposure. The object of interest must generate a signal, again in photoelectrons per pixel, that is measurably larger than this noise in the background. For example, a background of 10,000 photoelectrons per pixel has a quantum noise of 100 photoelectrons. This fundamental limit on the measurement is illustrated in more detail in Table 2, using parameters relevant to the instrument and measurement conditions relevant to ground based observing from a tropical site.

```
CCD pixel size     = 27 microns
Focal Length       = 140 mm
Aperture Dia.= d = 100 mm
Altitude = H       = 300 km
Pixel at H     = a = 60 meters
Pixel in radian    = 60/300,000 = 1/5,000 radian
Estimated atmospheric attenuation    = 0.5
Spectrograph or Filter transmission = 0.6
Optical                  "            = 0.8
Net Optical Eff.= K = 0.25
Quantum Efficiency, Qe = 0.66 (typical back illuminated CCD)
Object luminance = R in Rayleigh
```

1 Rayleigh = 8 x 10E4 photons/sq.cm/sec/steradian

Object Plane Pixel Area = a^2 = 3600 sq. meters = 3.6 x 10E7 sq.cm.

Aperture Area in Steradians = (d/H) = (0.1/300,000) = ~10E-13

$$\text{PixelExposure} = tRK\left(\frac{a\ d}{H}\right)\ 8 \times 10E8 \quad \text{photons/pixel/sec/Rayleigh}$$

Exposure = 0.06 R t for the above set of parameters.

For Qe = 0.66 photoelectrons per photon

Exposure = 0.04 R t photoelectrons/pixel/sec/R

The transfer function of the digital CCD camera is 1 ADU = 6.4 microvolt. The CCD on chip amplifier has a transfer function of ~0.64 microvolt per photoelectron. Thus 1 ADU = 10 photoelectrons.

It works out that for an exposure time of 140 seconds and pixel binning factor of 3 x 3, Exposure = 77 photons/pixel/R. Thus the overall camera system transfer function becomes 5 ADU per Rayleigh for this 140 second exposure and 3x pixel binning.

These equations are expressed in tabular form in the following table for a range of backgrounds measured in Rayleighs.

TABLE 2

R	t	Qe	pe/pix	bin 3x3	rms noise,pe	%	rms noise,R
2500	143	0.66	14,157	127,413	357 pe	0.29	7.0 R
2000			11,326	101,934	319		6.27
1500			8,494	76,446	276		5.44
1000			5,663	50,967	225		4.44
500			2,831	25,479	160		3.13
250			1,416	12,741	113		2.22

One notes that a 500 R background results in 25,479 photoelectrons with a square root of 160 electrons = rms quantum noise = 0.6 % = 500 x 0.006 = 3.13 R rms. Decreasing the exposure time by a factor of 9 to 16 seconds, increases the noise to 9.38 R, a factor of 3 corresponding to the factor of 9 decrease in the number of photoelectrons per pixel. This is the tradeoff between temporal resolution and background noise. Decreasing the binning from 3x to 1x results in a corresponding factor of 9 decrease in the number of photoelectrons per pixel and the same factor of 3 increase in background noise. In this case the pixel size changes from 180 to 60 meters square, so there is a tradeoff between spatial resolution and background noise.

The noise tabulated in Table 2 is the best that one can do, based on the physics of the problem. Other noise sources and inefficiencies will increase the background noise over what is shown in Table 2.

The situation can be improved by increasing the number of photoelectrons per pixel. This can be done by employing a larger optical aperture. Since there is a limit in the focal length to diameter ratio at about f/1 the only way to increase the diameter is to also increase the focal length of the optical system. For a given field of view, the image sensor must increase in proportion to the increase in the focal length and aperture diameter. In the instrument used for the July 92 CRRES measurements, the image

sensor was 512 x 0.027 = 13.824 mm square. Increasing the optical aperture to 200 mm would require doubling the linear dimension of the image sensor in order to maintain the 5.6 x 5.6 degree field of view. In return the noise would be reduced by a factor of 2 over the values listed in Table 2. Larger area CCD image sensors are commercially available.

Pixel Binning

The CCD can be operated in a way that allows the pixels to be summed vertically and horizontally prior to readout via its on-chip amplifier. This binning process involves adding the photoelectron charge accumulated in individual pixels (#pe) together in the readout process and generates negligible additional noise. On chip binning does require a digital camera with microcomputer control of the CCD readout process. It cannot be implemented on the analog CCD cameras currently used in the UV Imager. PSI designs and sells such digital CCD cameras for scientific applications.

This facility to bin pixels allows the size of the focal plane pixel to be selected for a particular observation to maximize the signal-to-noise ratio as a trade-off against spatial resolution, at a given optical focal length. The signal-to-noise ratio in a binned pixel is expressed in the following equation:

$$\frac{\text{Peak Signal}}{\text{RMS Noise}} = \frac{(\#\text{pe/pixel}, N)(\text{Binning Factor}, B)}{[\, NB + I_d B + R_n^2 \,]^{1/2}}$$

where I_d is the dark current per pixel and R_n is the rms readout noise per pixel in electrons. This points up the need for lower dark current in the binned mode in order to take maximum advantage of binning to improve the signal to noise ratio, i.e. $I_d B$ should be $< R_n^2$.